

## INVESTIGATIONS OF SHUTTLE MAIN LANDING GEAR DOOR ENVIRONMENTAL SEALS

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### Investigations of Shuttle Main Landing Gear Door Environmental Seals

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2005 Seal Workshop

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## Overview

- CAIB investigation and request for examination of Main Landing Gear (MLG) door seals
- NASA GRC's involvement in investigation
- Description of MLG door environmental seals
- Results from compression testing
  - Exploratory (installation/mounting conditions)
  - Systematic
- Results from flow testing
- Seal performance conclusions

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## Investigation of Main Landing Gear Door Seals

- Columbia Accident Investigation Board (CAIB) requested investigation of MLG door environmental seals
  - Assess potential contribution of seals to loss of STS-107
  - Assess safety issues of seals for future flights
- Environmental seals provide pressure-blocking capability to MLG doors
- Upstream thermal barrier not investigated in this study



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The Columbia Accident investigation Board (CAIB) requested an investigation into the MLG door seals. Initially, the MLG door seals were thought to have been a potential contributor to the loss of Columbia. These suspicions were later found to be untrue, but the seals remained as a cause for concern in future flights.

MLG door seals comprised of thermal barrier and environmental seal. This study focuses on the environmental seal for the MLG door. Photograph shows the installed environmental seal on the MLG door. Tape behind seal is removed before door closure.

## Findings from Investigation of MLG Door Seals

- Installation and maintenance procedures problematic
  - Seal compression specified in certification documents
  - Compression procedures not specified in installation/rigging drawings
  - Seal maintenance procedures not specified between flights
- Damage to seals
  - Permanent deformation of seal bulb from OV-103
  - Clay compression test demonstrated seals did not meet certified compression requirements



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The investigation into the Shuttle MLG door seals found several problems with the seals.

First, the installation and maintenance procedures were found to be potential problems. The seal certification documents specified the minimum amount of compression to be applied to the seals (after maximum flight deflections of the MLG door), but neither the seal installation drawings nor the door rigging drawings provided any procedure to ensure that this minimum compression be met. Furthermore, no maintenance drawings or procedures existed for the seals, such that there were no documented means to ensure that the seals continued to be compressed to their certified compression levels, either by adjustment or measurement & replacement of the seals.

In addition, the investigation found that the seals installed on OV-103 (Shuttle Discovery) were permanently deformed and damaged from repeated use. The damaged varied from a small amount of deformation (“good”, right) to heavy deformation (“bad”, left). Clay compression tests demonstrated that the damaged seals did not meet certified seal compression requirements.

## Replacement of Seals and Subsequent Problems

- Steps to satisfy seal certification documentation
  1. Old (Rev. M) seals replaced with new (Rev. P) seals
  2. Shims added to sealing surface to ensure proper seal compression
- Modifications prevented full closure of MLG door
  - Door retraction mechanism linkage near-overload
  - Previous experience (ca. 1991) demonstrated that overload conditions damaged door retraction linkage mechanism
- NASA Johnson Space Center (JSC) requested testing of MLG Environmental Seals at NASA Glenn Research Center (GRC)

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Several steps were taken to alleviate the potential problems with the environmental seals.

The old Rev. M seals were replaced with new Rev. P seals to eliminate permanent deformation. In addition, constant-thickness shims were added to the sealing surface (MLG bay) to ensure that the seals would always be compressed to their certified amounts after accounting for maximum flight deflections of the MLG door.

However, after making these modifications, the MLG doors could not be closed. The modified seals generated loads approaching mechanical limits on the door retraction mechanism linkages. Previous experience (ca 1991) had demonstrated that higher preloads caused damage to the linkage, and thus engineers were reluctant to increase the preload on the linkages to close the MLG door.

At this point, NASA JSC requested that NASA GRC conduct tests of the MLG environmental seals.

## Involvement of NASA GRC

- Exploratory compression testing to assist in closing MLG doors
  - Understand mounting and setup effects on seal loading
  - Provide options for reduction in seal loading
- Systematic testing
  - Fill out seal performance database
    - Compression
    - Flow (0%-63% compressions)
  - Determine new seal (Rev. P) performance relative to old seal (Rev. M) performance

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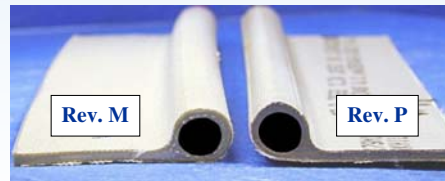
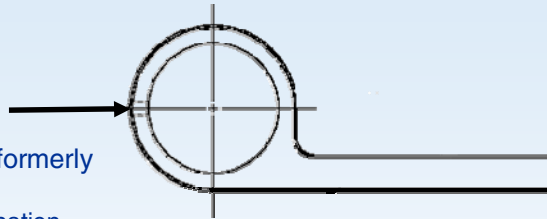
NASA GRC's testing of the MLG seals was performed in two parts with two primary goals.

First, exploratory tests were conducted on the seals to understand the loading characteristics of the seals. These exploratory tests were to investigate installation variables on the seals and would ultimately provide options to reduce the amount of load generated by the seals.

After the exploratory tests, a series of systematic tests were conducted. The seal performance database was incomplete in both compression and flow data, and GRC's testing rectified this. In addition, the GRC tests determined the performance of the new Rev. P seal relative to the old Rev. M seal. If the Rev. P performance closely matched Rev. M performance, the new seal would be shown to meet the certification requirements and would not have to be recertified (a lengthy procedure).

## Description of MLG Environmental Seal

- Silicone rubber core
- Nomex fabric overwrap
- Vent holes every 6 in.
- Two revisions
  - Rev. M - old revision (formerly flown)
    - Nomex fabric impregnation
    - Higher stiffness
  - Rev. P - new revision (installed on STS-114)
    - Material slightly darker than Rev. M
    - No Nomex impregnation
    - Lower stiffness



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The Orbiter MLG environmental seal is made of a hollow bulb section attached to a solid tail section. Both are composed of silicone rubber (ZZ-R-765, Class IIIa, Grade 50) overwrapped with Nomex fabric.

Since the seals are designed to work in space (i.e. vacuum conditions), vent holes are included every 6 in. in the front of the seal bulb. These holes allow pressure in the interior of the bulb to vent to ambient pressure, preventing damage to the seals.

Two revisions of the seal were tested in this study. The old type of seal, Rev. M, was removed from OV-103 during the initial investigation of the seals. It features an additional Nomex fabric impregnation of the silicone rubber material, particularly in the bulb.

The new seal revision, Rev. P, lacks the Nomex fabric impregnation of the silicone rubber. The lack of Nomex impregnation leads to a seal which is less stiff to the touch than the old Rev. M seal. The Rev. P seal material is also a slightly darker color than Rev. M, indicating a possible change in composition of the silicone rubber.

## Damage to Rev. M Seals Removed from OV-103



- Seal samples removed from starboard MLG door
- Samples represented extremes of damage
  - “Good” seal deformed ~0.035 in.
  - “Bad” seal deformed ~0.110 in. - 0.160 in.
- Sample locations
  - “Bad” seal taken from hinge side of door
  - “Good” seal taken from rear of door

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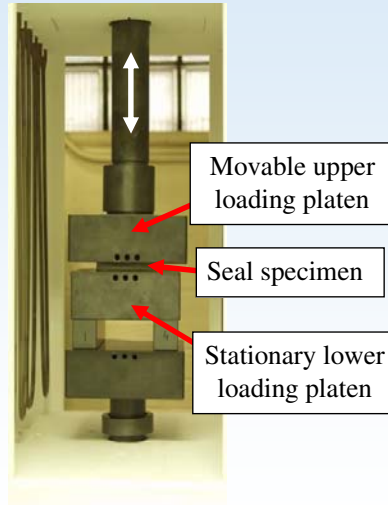


In addition to the as-received Rev. M and Rev. P seals tested in this study, seals removed from the starboard MLG door of OV-103 were also investigated. Specimens representing the extremes of damage to the Rev. M seal were taken. The “good” specimen was measured to be deformed approximately 0.035 in. relative to a pristine specimen, while the “bad” seal showed heavy damage with deformations varying between 0.110 in. and 0.160 in.

The “bad” seal was taken from locations along the hinge line of the door, while the “good” seal was removed from the rear of the door.

## Description of MLG Seal Compression Testing

- Measure load vs. compression
- 5-in. length of MLG door seal
- Room temperature compression tests
- Exploratory testing
  - Understand loading conditions
  - Recommendations for reduction in seal load generation
  - Select setup/mounting conditions for systematic tests
- Systematic testing
  - Compare Rev. P to Rev. M
  - Fill out seal performance database



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Compression testing on the MLG seals was conducted in NASA GRC's Compression Rig. The rig consists of a movable upper and stationary lower loading platens. The seal specimen is placed between the two platens and compressed by the upper platen. Generated load is measured by a load cell in-line with the lower platen, and compression is measured by an LVDT connected to the upper platen. All compression specimens in this study were 5 in. in length.

The first set of tests were exploratory tests to better understand the mounting conditions of the MLG seals. After these tests, GRC provided JSC/KSC with recommendations to decrease seal load generation and allow closure of the MLG doors.

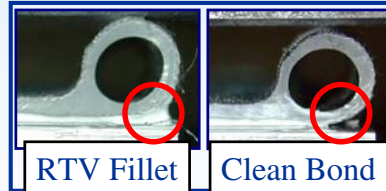
The systematic testing was performed to compare Rev. M seals to Rev. P seals and demonstrate that the Rev. P seals serve as an acceptable substitute for the Rev. M seals. Additionally, the systematic tests were designed to fill out the seal performance database for future reference.

## Exploratory Testing Variables

- Effect of Groove



- Effect of RTV fillet



- Effect of loading speed

- 0.002 in/sec
- 0.200 in/sec

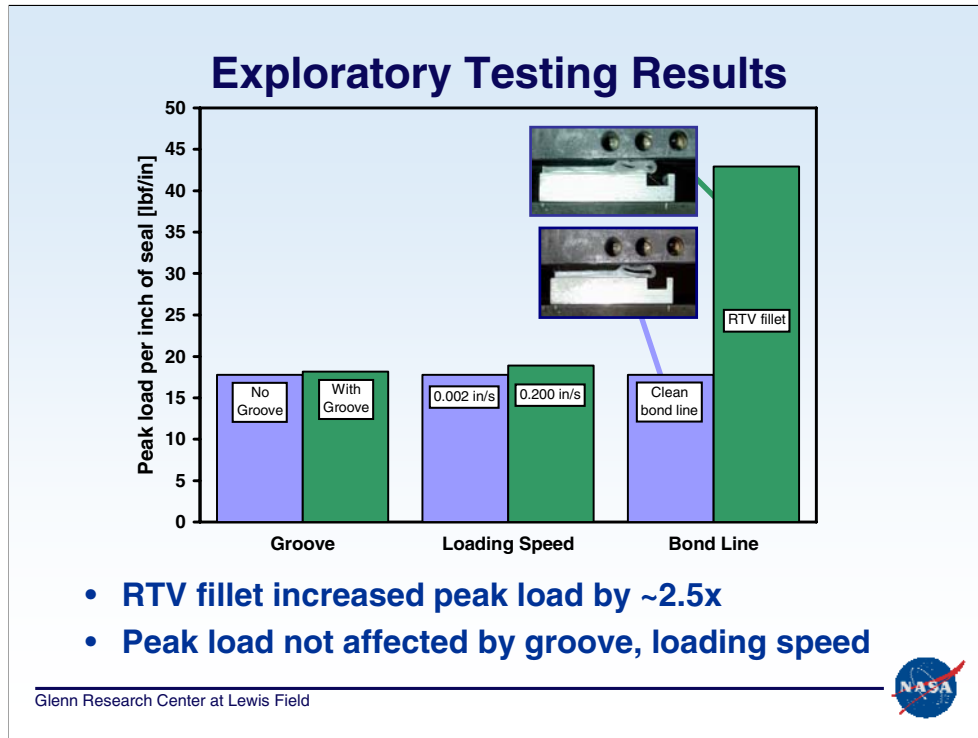
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Three variables were examined during the exploratory tests. First, the presence of a groove adjacent to the seal bulb was evaluated. Actual Orbiter mounting conditions include the groove.

Second, the presence of an RTV fillet under the seal bulb was examined. Excess RTV was observed along the seal bulb in the newly-installed seals on OV-103.

Finally, the speed at which the seals were loaded was varied between 0.002 and 0.200 in/sec. The doors typically close quickly, so that the faster loading speed is believed to be a better representation of Orbiter conditions than the slow speed.



Compression results for exploratory tests with only the first cycles of each test shown. The graph is % compression vs. load generated in the seal, and the arrows indicate the different paths for loading and unloading portions of the testing cycle. The first five tests show results which are nearly identical, demonstrating that the presence of the adjacent groove and the seal loading speed do not affect the test results. The sixth test (blue curve) demonstrates that the presence of the RTV fillet increases the load by as much as a factor of three.

## Findings from Exploratory Tests

- Implications for Return to Flight
  - GRC recommended removal of RTV fillets from OV-103 seals
  - Seal installation procedure amended to include removal of excess RTV
- Systematic test variables selected as:
  - 0.200 in/sec loading
  - Groove adjacent to seal bulb
  - No RTV fillet

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GRC recommended to JSC/KSC that removal of excess RTV from under the seal bulb would reduce generated loads and possibly allow MLG door closure. The seal installation procedures were amended to include the removal of excess RTV.

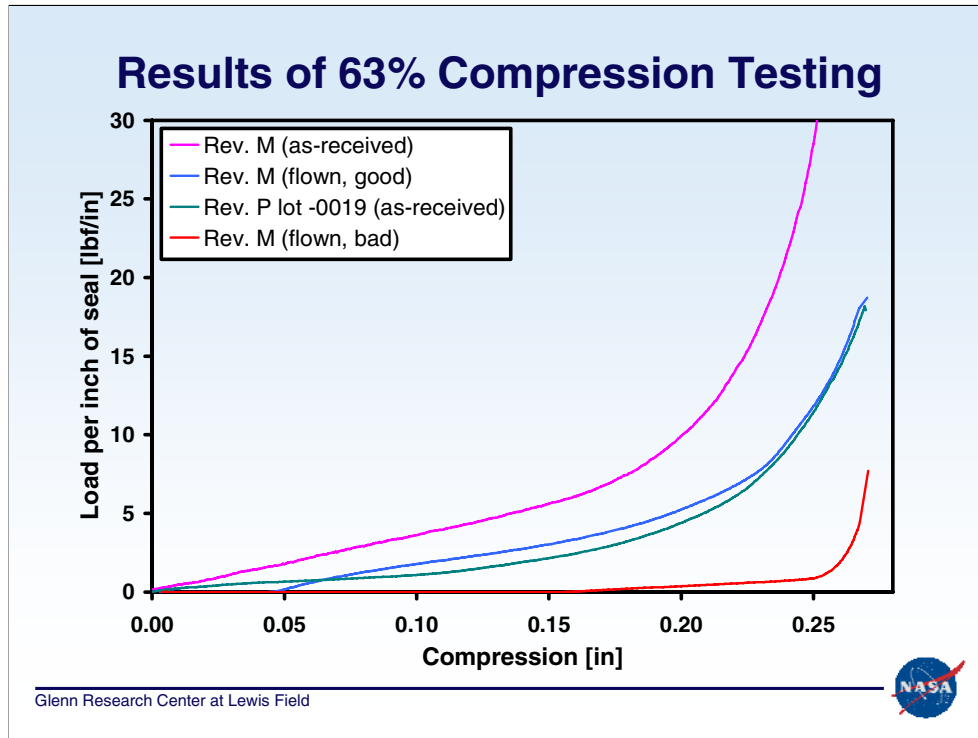


Chart shows results from four seals (two as-received, two flown) for systematic compression tests. The graph is compression distance [in] vs. generated load per inch of seal. The as-received Rev. M data is plotted twice: once in its as-measured state, and once shifted to the right (i.e. higher compression) by 0.035 in.

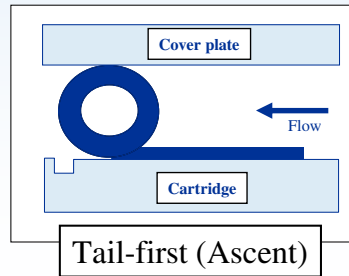
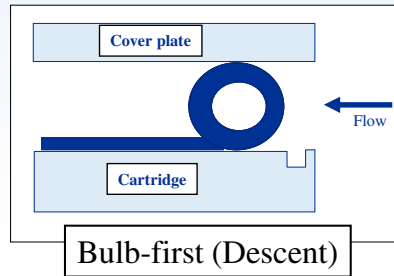
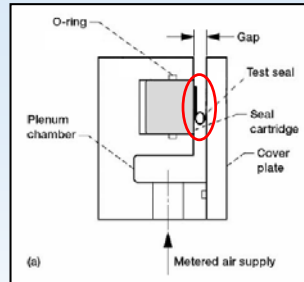
The as-received Rev. M specimen demonstrated the highest loads of the specimens tested, and the “bad” flown Rev. M demonstrated the lowest. With approximately 0.160 in. of permanent set, the “bad” flown specimen did not generate load until the upper platen contacted the bulb.

The as-received Rev. P data falls far below the as-received Rev. M specimen and is even lower than the “good” flown seal data. The reduction in generated load may be due to the lack of Nomex impregnation of the seal bulb. The as-received Rev. M seal generated five times the load of the as-received Rev. P seal for 63% compression.

**What does this mean?** Rev. P seals may be used as replacements for Rev. M seals without danger of overloading Shuttle structures. As-received Rev. P seals can be expected to generate lower loads (as much as five times) than as-received Rev. M seals. Permanent deformation in the seal bulb reduces the load generated by the seal.

## Description of MLG Seal Flow Testing

- Flow rate measured as a function of:
  - Pressure drop across seal
  - Seal compression
- Two specimen orientations



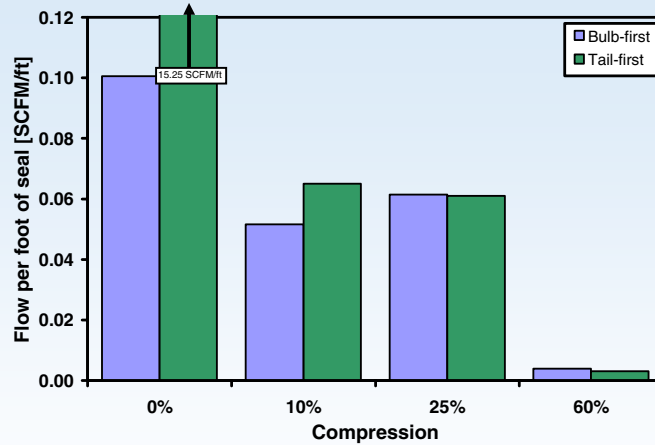
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Seals in the bulb-first orientation are pressurized similarly to those on shuttle descent when the pressure outside the MLG bay exceeds that inside the bay.

Seals in the tail-first orientation are pressurized similarly to those during shuttle ascent when the pressure inside the MLG bay exceeds that outside the bay.

## Flow Test Results (Rev. P Seal)



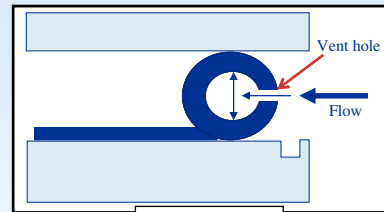
- Bulb-first (descent) flow rates below 3 SCFM/ft leakage limit
- Tail-first (ascent) flow rates much higher at low compressions
- Effect of orientation disappears by 25% compression

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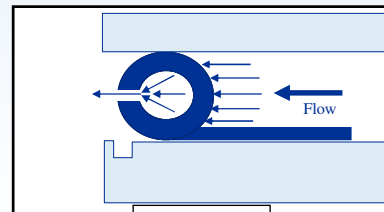


## Seal Bulb Pressurization Effects

- Bulb inflation occurred via vent holes in bulb-first orientation
  - Stagnation pressure raised bulb pressure
  - Improved bulb contact along sealing surface
- Bulb deflation occurred via vent holes in tail-first orientation
  - Pressure along rear of seal bulb deflated bulb
  - Bulb deflation opened gap along sealing surface



Bulb-first



Tail-first

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## Flow Testing Summary

- Bulb-first seals met flow certification requirements
  - Leakage below 3 SCFM/ft for all compressions
  - Bulb inflation reduced seal leakage rates
- Tail-first seals met flow certification requirements for higher compression levels
  - Leakage below 3 SCFM/ft for compressions greater than 5%
  - Bulb deflation may have increased leakage rate below 5% compression
- Plateau or increase in Rev. P flow data between 10-25% compression



## **Actions Taken by JSC/KSC**

- Removal of excess RTV allowed closure of starboard door
- Two actions to successfully close port-side door
  - Custom-thickness shims added to sealing surface (replaced constant-thickness shims)
  - Door retract link shortened to increase preload
- Future steps to ensure compliance with certifications
  - Seal installation procedures amended to include removal of excess RTV
  - Seal deformation to be checked between flights

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## Conclusions

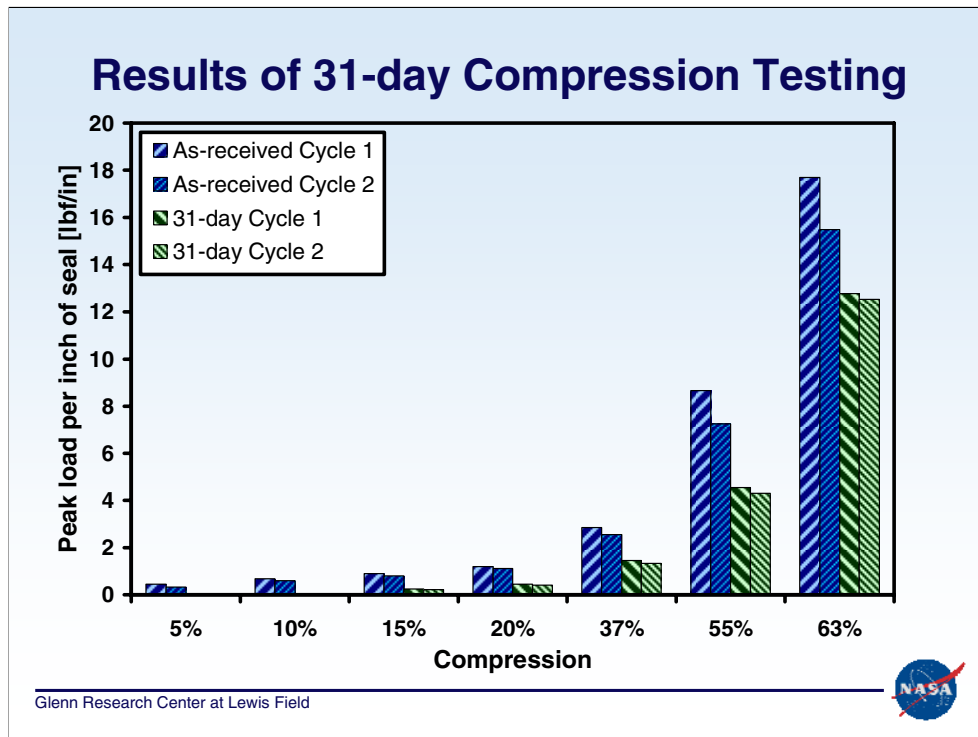
1. Excess RTV at bond line increased peak loads by ~3x
2. As-received Rev. P seals generated less load than as-received Rev. M seal
3. Leakage rates of Rev. P seals were below 3 SCFM/ft leakage limit for compressions greater than 5%
4. Seal bulb inflation may improve seal performance during reentry pressurization



## Systematic Compression Tests

- Basic compression tests
  - 63% compression
  - Held for 30 seconds, then released
  - Repeated once
- 31-day test
  - 63% compression for 31 days (uninstrumented)
  - Measured load at discrete compression levels





This graph shows the peak load per inch of seal vs. discrete compression levels applied to the seals for each of the two loading cycles. Both seal previously held at 63% compression for 31 days and an as-received control specimen are shown. The as-received specimen was measured to have 0.050 in. (12%) permanent deformation after release from the 31-day compression fixture.

The control specimen generated small amounts of loads immediately, while the 31-day compressed specimen did not generate any measurable load until 15% compression. Since the 31-day specimen was found to have 12% permanent deformation after the compression, the upper platen of the fixture did not contact the seal for 5% and 10% compression and generated no load for these displacements. Meanwhile, at 63% compression, the first cycle of the post-compression specimen generated 80% of the load of the as-received specimen.

Of particular interest was the drop-off in load of the as-received specimen between the first and second loading cycles and the relatively small load reduction in the compression specimen. If load drop-off is assumed to be proportional to permanent deformation, the data indicates that a seal with permanent deformation takes on new deformation more slowly than a pristine seal.

**What does this mean?** Seals held at compression for 31 days will take on some permanent deformation (0.050 in. in this test). However, the rate at which the seals take on permanent deformation appears to decrease as the seal takes on more deformation.